DISTRIBUTED SOFTWARE DECISION SUPPORT SYSTEMS FOR HETEROGENEOUS COORDINATION IN CHEMICAL AND BIOLOGICAL RESPONSE

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ABSTRACT

During detection and response to a Chem-Bio incident, heterogeneous groups, who may not ordinarily interact, must form a team. A Sensible Agent is a type of *software agent* (a Distributed Artificial Intelligence component that uses sensing, reasoning, and acting capabilities to achieve a set of goals) with additional coordination capabilities. For the Chem-Bio terrorism domain, Sensible Agents can offer the following decision-support capabilities: (1) belief revision based on models, certainty and the trustworthiness of incoming information sources, (2) situation-based recommendations on the composition of decision-making groups, the relative strength of members of the group and over whom the group has authority, and (3) planning and resource allocation. This paper describes possible benefits of applying a Sensible Agent system to provide Chem-Bio detectors and responders with *in situ* decision support for task and resource management.

1 INTRODUCTION

Acts of biological and chemical terrorism may be hard to predict, to detect, and to remedy. Both detection and response involve highly dynamic, uncertain, and complex scenarios. Especially in Chem-Bio response, many groups are involved with diverse and sometimes conflicting goals. The use of intelligent software agents as decision support tools can mitigate some of these problems. An intelligent agent is a type of distributed artificial intelligence that plans, models its environment, and has some degree of autonomy to achieve a set of goals. A Sensible Agent is an agent that can reason about the decision-making frameworks it uses to achieve its goals; which affect its level of autonomy over decisions about action selection.

This paper envisions the application of Sensible Agents to the domain of detection and response to a chemical or biological terrorism incident, allocating a Sensible Agent to each decision-maker who must assess incoming information, determine appropriate actions and take action. Sensible Agents are designed so that an agent can integrate distributed information sources and create plans of action based on acquired information and derived situation assessment. A Sensible Agent uses awareness of the situation -- other agents, the status of communication, and other environmental conditions -- to find the best decision-making framework for each goal. A decision-making framework (DMF) describes the interactions, if any, of a group of agents as the group works to determine how to achieve a goal. A DMF specifies (1) the amount of decision-making control each agent has over how each goal should be achieved and (2) which agents are bound to follow the decisions. Prior research has shown that agents

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using Adaptive Decision-Making Frameworks (ADMF) can achieve better system performance in uncertain, dynamic worlds [1].

During the detection of a biological terrorism event, a Sensible Agent could assimilate multiple, heterogeneous information sources and develop beliefs about the certainty and trust-worthiness of such information. Even a small Chem-Bio response brings together many independent groups, such as fire departments, local, state, and federal law enforcement agencies, local and state health departments, public and private hospitals, and city office of emergency management in a situation where none may be fully capable to respond and manage the incident alone. Each of these groups has skills, equipment, manpower, training, and contacts they can apply towards handling the situation. However, the groups may also have conflicting subordinate goals under the common goal of mitigating the effects of the incident. Additionally, these groups may work together infrequently and only in training or situations with little in common with a particular incident. Even when groups share the same goals, they may conflict with each other in the execution of those goals. Coordination among these groups is difficult, but clearly necessary for a successful response to a Chem-Bio incident.

Other researchers in the field have published some related research. Leake et al. discuss the application of case-based reasoning to generate simple disaster response plans from short textual descriptions of events [2]. Simonovic discusses the design and deployment plan of an automated decision support system for sustainable flood management in Winnipeg, Canada [3]. Grathwohl et al. discuss the application of description logics in the domain of forming disaster management response plans [4]. The ENCOMPASS system, a DARPA project, focused on consequence management for first responders in Chem-Bio terrorism, routine fire, and hazardous materials incident response [5]. Schreckenghost et al. have applied a design philosophy known as Adjustable Autonomy, which is similar in some ways to the Adaptive Decision Making Frameworks (AMDF) described herein, to monitoring and controlling life support systems for NASA [6]. However, Adjustable Autonomy lacks some of the flexibility and power of AMDF. While Adjustable Autonomy allows the developer or the user to adjust the distribution of decision-making control between a human user and automated system, ADMF gives any human or autonomous decision-making agent some control over the distribution of decision-making control among a system of human and automated decision makers.

To illustrate the utility of ADMF and the potential application of Sensible Agents to Chem-Bio terrorism detection and response, the remainder of the paper is organized as follows. Section 2 gives a brief overview of the organization and operation of the Sensible Agents Architecture. Section 3 presents an application of Sensible Agents during the detection phase of a Chem-Bio incident, and Section 4 continues the example scenario by showing how Sensible Agents could be applied during the response phase. Section 5 concludes.

2 SENSIBLE AGENT ARCHITECTURE

Sensible Agents have been designed and implemented to operate in dynamic, uncertain worlds. The reader should consider the possible application of a Sensible Agent tied to each decision maker conducting bio-surveillance and coordinating Chem-Bio incident response The Sensible Agent logical architecture, shown in Figure 1, is composed of four modules, each of which provides a distinct set of functionality for the agent. All information from the environment is filtered through a set of formally defined sensors. Sensible Agents are capable of responding deliberately and reactively to fulfill their goals in the context of sensed environmental changes. Each Sensible Agent sends all actions (e.g. communication, movement, etc.) to a set of actuators that passes information to the environment. The sensor and actuator suites provide a layer of abstraction and a well-defined interface between Sensible Agents and their environment.

The ***Perspective Modeler*** (PM) contains the agent's explicit model of its local, subjective viewpoint of the world. The model includes behavioral, declarative, and intentional models of the agent itself, other agents, and the environment [7]. The behavioral model specifies the current state and possible transitions to other states, which are represented using an Extended State Chart (ESC) [8]. The declarative model holds a set of facts represented as name-value pairs. The agent intentional model includes the Intended Goal Structure (IGS), which represents the goals an agent intends to achieve [9]. The PM interprets

internal events and information obtained through sensors and communication, allowing the agent to sense environmental change, store relevant information in the declarative model, and update the behavioral model accordingly.

The ***Action Planner*** (AP) interprets domain-specific goals, plans to achieve these goals, and executes the generated plans [10]. The AP uses a suite of actuators to act on the environment, which in most domains includes a communication actuator for sending messages to other agents in its system.

The ***Autonomy Reasoner*** (AR) determines the appropriate decision-making framework (DMF) for each of the self-agent's goals. An agent's collaborative decision-making behavior is constrained by how it participates in a given framework. Figure 2 shows the different interaction styles an agent can employ within a decision-making framework: (1) ***Command-driven***— the agent does not make decisions and must obey orders given by a master agent, (2) ***Consensus***— the agent works as a team member, sharing decision-making equally with other agents, and (3) ***Locally Autonomous/Master***— the agent makes decisions alone and may or may not give orders to other agents. These DMFs constrain the collaborative problem solving of the AP. Sensible Agents use a form of dynamic reorganization called Adaptive Decision-Making Frameworks (ADMF), which allows agents to form, dissolve, and modify decision-making interactions with other agents. The effectiveness of decision-making frameworks can vary across situations. ADMF allows agents to employ the most effective decision-making framework in any given situation [11].

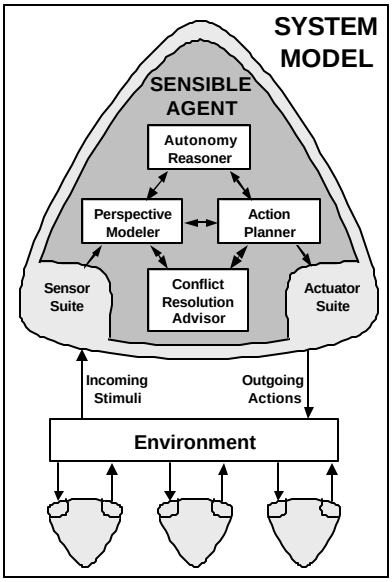

Figure 1: The Sensible Agent architecture.

The ***Conflict Resolution Advisor*** (CRA) identifies, classifies, and generates possible solution strategies for conflicts between agents. The CRA monitors the AP and PM to identify conflicts. Once a conflict has been detected, it classifies this conflict and suggests a resolution strategy (voting, negotiation, arbitration, self-modification) to the AP. The appropriateness of each strategy varies based on the situation [12].

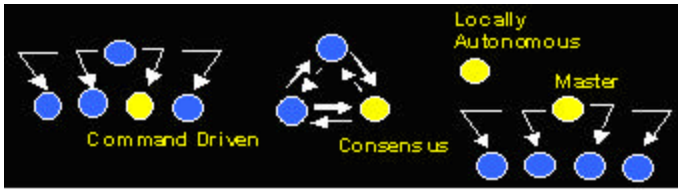

Figure 2: Interaction styles individual Agents use within Decision-Making Frameworks.

The AP, AR, and PM all use of inter-agent communication in their operation. The AP and AR use communication for inter-agent coordination, while the PM communicates to share knowledge. Communication, like all other interactions with the agents' environment, is carried out via actuators and sensors. Sensible Agents use KQML as the basis for their inter-agent communication language [13].

Sensible Agents not only react and plan to influence the state of the world, but also explicitly reason about the beliefs of other agents and search for an optimal decision-making framework as the world changes dynamically. These capabilities make Sensible Agents particularly appropriate for domains where agents' actions greatly affect one another and the cost/benefit tradeoffs of DMFs may change.

3 SENSIBLE AGENT APPLICATION TO BIOLOGICAL TERRORISM DETECTION

This section presents a bio-surveillance scenario and illustrates how a Sensible Agent-based system could be used for decision support throughout the scenario. During bio-surveillance, Sensible Agents could assist in information collection, analysis and propagation. A Sensible Agents approach can provide

high-level sensor fusion and situation-aware assessment to supplement the traditional techniques of information analysis automation.

The Center for Disease Control is facilitating and funding the formation of state health alert networks to bring together information from traditionally under-utilized or unavailable health indicators, such as school attendance, pharmacy sales, and EMS dispatch calls [14]. Currently, some health information is mailed to state departments of health (DOH). Under the new system, epidemiologists will have access to a much larger amount of information much more quickly. The increased volume of information flowing into the DOH will necessitate more automated filtering, and the Texas DOH is currently evaluating several methods for this automation.

This example scenario follows the pattern used in many biological terrorism tabletop exercises [15]. A contagious respiratory disease is released on Day 0 at a large public event. The attack is unannounced and undetected. The disease incubates during Day 1 without any visible indicators. On Day 2, many students are absent from school, EMS dispatches for respiratory problem are abnormally high, and pharmacies sell a lot of decongestants. Additionally, hundreds of people present themselves to medical facilities, are assessed as having a flu-like illness and are released. The information from Day 2 is comes into the DOH during the late afternoon and evening hours of Day 2 and the early morning hours of Day 3.

What role could a Sensible Agent based system play at this point? A Sensible Agent could assist each decision maker in a network of automated systems and human epidemiologists analyzing the health information for a bio-surveillance effort. Sensible Agents could provide decision support by building models of the indicative trust-worthiness of information sources, combining disparate sources of possibly conflicting, incomplete, and uncertain information to form a coherent picture, notifying off-duty DOH staff members after initial analysis and planning allocation of computational and other resources. The following sections focus on the application to a bio-surveillance task of three Sensible Agents modules, the Perspective Modeler (PM), Autonomy Reasoner (AR), and the Action Planner (AP).

3.1 PERSPECTIVE MODELER (PM)

Sensible Agents employ the Perspective Modeler (PM) to assess the state of itself, other agents, and the environment based on incoming information from multiple types of sources, e.g. other agents, humans, databases, and other automated systems. A valid analysis should attend to important relationships within the information. For example, different sources of information may confirm or refute one another. Pure statistical techniques often assume independence of data; however, it is exactly the dependencies among information that can allow disambiguation. The PM uses semantic networks to model the relationships among information. As information comes into the system, the conclusions drawn from previous information may become more or less likely, or even impossible. For instance, a lab test may conclusively rule out a disease, even if all other factors strongly indicated it.

When two sets of information are directly contradictory, one must disregard one or the other to use either. The question is, which one to trust? The PM assigns a reputation to each source of information, giving a higher reputation to sources that have proven accurate or trustworthy and

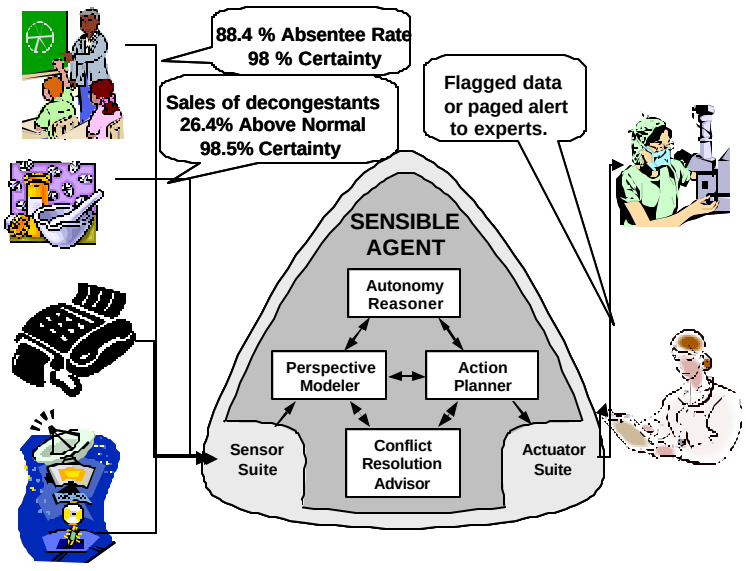

Figure 3: Sensible Agent supports decision makers by combining information sources and alerting staff.

decreasing its trust in faulty, dishonest, or imprecise sources. Thus, when new information arrives from a source, the PM uses Bayesian techniques to model the certainty of information based on its reported certainty and the PM's modeled reliability of the reporting information source [16].

Additionally, the PM could initiate queries for more information when it deems necessary. For example, the PM of Agent1 could notice that it does not have enough information to make a certain classification of an incident, but that another agent, say Agent2, has additional relevant information. The PM would then send a message through the AP to Agent2, requesting that Agent2 send more information to Agent1. Agent1 may then have enough information to make a justifiably assured classification of the state of the world. Because the PM models it own and others' current states and the viable transitions between states, the PM can provide reactive plans specifying a set of actions which transition the agent from its current state to a desired future state.

3.2 AUTONOMY REASONER (AR)

For each goal a Sensible Agent is pursuing, the Autonomy Reasoner assigns a decision-making framework (DMF) specifying which agents can make a decision about that goal and which agents fall under their authority for that decision. For Chem-Bio terrorism, one important application of decision-making frameworks concerns the goal: "Classify each set of information as a potential biological incident, natural epidemic, or inconsequential information anomaly." A Sensible Agent monitoring this process must decide when the automated system can classify the information on its own and when the system should flag it for further review by a human epidemiologist. Each time the agent has the goal of classifying a set of information, the agent must assign a DMF to the goal: **Locally Autonomous** if the agent can assess the information on its own, or **Consensus** or **Master/Command-Driven** if the agent defers some or all of the decision to another agent, such as a human expert. Using a learning technique such as case-based reasoning, a Sensible Agent could learn from experience when to defer decisions to a human or when to assume full responsibility for the decision.

3.3 ACTION PLANNER (AP)

The Action Planner (AP) generates and executes a course of action; for example, the AP could determine whether the agent should page an off-duty epidemiologist or merely flag the information for review in the morning. The AP selects an action based on the PM's assessment of the current state and the AP's assessment of how to best achieve a desired future state. The AP creates, picks, and executes a plan of action based on the decision-making framework chosen by the AR. During bio-surveillance, the AP could also allocate computational resources to analyzing different sets of information based on the PM's situation assessment of the information.

4 SENSIBLE AGENT APPLICATION TO CHEM-BIO TERRORISM RESPONSE

Continuing the scenario, how could Sensible Agents help during the response phase of a Chem-Bio incident? During response, heterogeneous groups possibly including local, state, and federal civilian and military organizations, which may not ordinarily interact, must form a team. Each group provides a set of skills, equipment, and facilities that must be coordinated in the response. Sensible Agents can assist with response, especially with the coordination of a heterogeneous team. A Sensible Agent-based system could perform belief revision, team building combined with facilitating unified command, resource allocation, and conflict detection and resolution.

Many regions already use the Incident Command System (ICS) to coordinate during Hazardous Materials incidents, large fires, and other multi-jurisdictional events [17] [18]. ICS is a set of guidelines, terminology, and forms for organizing the command of such incidents that scales with the size of the event. For instance, for small events, one person may handle all financial concerns. As the response grows, some of the responsibilities of that person are delegated to a hierarchical staff built up as demand necessitates. When the event begins to wind down, the command structure shrinks with it, progressively concentrating tasks into fewer people. In addition to the original ICS designed primarily by fire departments, specialized versions have been created for law enforcement (LEICS) and health care (HEICS), although all types of organizations can collaborate within the classic ICS framework [19]. Using the capability of Adaptive Decision-Making Frameworks, a Sensible Agent-based system could be used to both simulate and recommend dynamic changes in coordination for Chem-Bio incidents.

4.1 PERSPECTIVE MODELER (PM)

The Perspective Modeler plays much the same role in response as in detection. As the situation dynamically unfolds, especially with inadequate communications and rapidly changing conditions, the ability to derive a centralized global assessment is greatly diminished, if not impossible. Each decision maker must be capable of good local situation assessment – creating a sufficient coherent view from what information is available, even if it is inconsistent. The lack of such good intelligence summaries and intra-agency communication conduits was one of the driving forces behind ICS [18]. The PM could integrate information sources from across an event to form a status report based on declarative and behavioral models of events and to point out inconsistencies in reports. Trust metrics can play a greater role, as there might be more unknown and untrusted agents, such as untrained volunteers.

4.2 AUTONOMY REASONER (AR)

The Autonomy Reasoner could help coordinate the disparate groups in a Chem-Bio response. Not only does the structure of organizations change along with the organization, but the people filling those roles may also change. The AR could propose decision-making frameworks apportioning authority in a way appropriate to the current situation. The AR can propose decision-making frameworks based on timing and deadlines, information-based situation assessment, mandated rules (for instance, mandates specifying that certain organizations must have primary decision-making control in some situations), and a database of easily retrieval experiences specifying what command structures worked best in similar past experiences. Additionally, the AR may facilitate the establishment of agreements between agencies to share authority over scarce resources through various types of decision-making frameworks.

4.3 ACTION PLANNER (AP) AND CONFLICT RESOLUTION ADVISOR (CRA)

Inadequate joint planning and resource management were also relevant problems. The AP and CRA modules can assist with generating efficient, conflict-free action plans and resources allocations. The AP could serve as a decision support tool for Command, Operations, Planning, and Logistics staff. Alternatively, it could act directly, for instance ordering supplies on the internet for the Support Branch of the Logistics Section. The CRA serves within a Sensible Agent as an integrated plan checker. The CRA can watch for conflicts between the planned actions of agents intending to work together within a DMF. For detected conflicts, the CRA can suggest resolution strategies.

5 CONCLUSIONS

The detection of and response to a Chem-Bio incident involves efficient management of complexity, dynamism and uncertainty. As the situation changes in Chem-Bio events involving many decision-makers assessing large amounts of variously reliable data, decision-makers must have the ability to change decision-making frameworks (e.g. change who is involved in a decision, their relative strength in the decision-making process, and to whom the group can dictate orders) based on the capabilities and objectives of each decision-maker. Sensible Agents can be applied to engineer a decision support system providing (1) Belief revision based on synthesis of information from multiple information sources using evaluation of trust-worthiness based on information certainty and the reputation of the source providing the information, (2) Dynamic, situation-based assessment of the best decision-making group formations (e.g. who should be making decisions, who should be taking orders), and (3) Distributed, coordinated planning and execution (e.g. resource allocation). In the face of unexpected situations, deadlines, changing priorities, unreliable communication, and scarce resources, Sensible Agents are flexible in the way they make decisions, integrate information, and plan. With these capabilities, the application of Sensible Agents to assist in the detection of and response to a Chem-Bio incident is promising.

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